Extreme Values of Wind Speeds over the Great Belt Region

Jensen, N.O.; Nielsen, B.

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Extreme Values of Wind Speeds over the Great Belt Region

N.O. Jensen and B. Nielsen

Risø National Laboratory, DK-4000 Roskilde, Denmark
October 1989

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Extreme Values of Wind Speeds over the Great Belt Region

N.O. Jensen and B. Nielsen

Abstract. A little more than 10 years of wind data measured at the height of 70 m above a small island has been used to estimate the wind speed at the expected 50 year return period. The finding is 32 m/s which is considerably smaller than the Danish wind code. Further reduction to $\sim$ 27 m/s is obtained when the projection perpendicular to the projected bridge is considered.

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Contents

1 Introduction

The present analysis searches for extreme values of wind speeds. The data material was obtained from a 70-m mast on a small island, Sprogø, in the middle of the Great Belt. Wind speed is here understood as a 10-min average value measured at that level. The actual measurements began in September 1977, and the analysis is carried out on the basis of data gathered until January 1988. The wind speed and direction were measured by instruments as described in Busch et al. (1979). A description of the meteorological station, the data, and a general analysis of the data are given in Jensen et al. (1988).

The number of storm cases per year is of course not constant, but on the other hand the variation over the years considered appears statistically stationary. The storm criterion is defined below, but as shown in Fig. 1 about 11 cases per year have speeds above 20 m/s, with a standard deviation of ± 3. Even for larger thresholds the distribution is fairly even as seen in Table 1.

Table 1: Number of cases with storm speeds larger than the designated value.

u (m/s)>	24	26	28
Year			
1977	2	1	0
1978	1	0	0
1979	1	0	0
1980	2	0	0
1981	4	2	1
1982	2	1	0
1983	2	1	1
1984	3	1	0
1985	3	1	0
1986	1	0	0
1987	2	1	1

The data from the year of 1977 do not comprise a full year, since data were collected from the beginning of September only, but as can be seen from Table 1 and Fig. 1 it is not very different from the others. However, in the below extrapolation to average 50-year events we assumed the present material to cover a 10-year period only. This is a conservative assumption regarding the strength of the extrapolated wind speed.

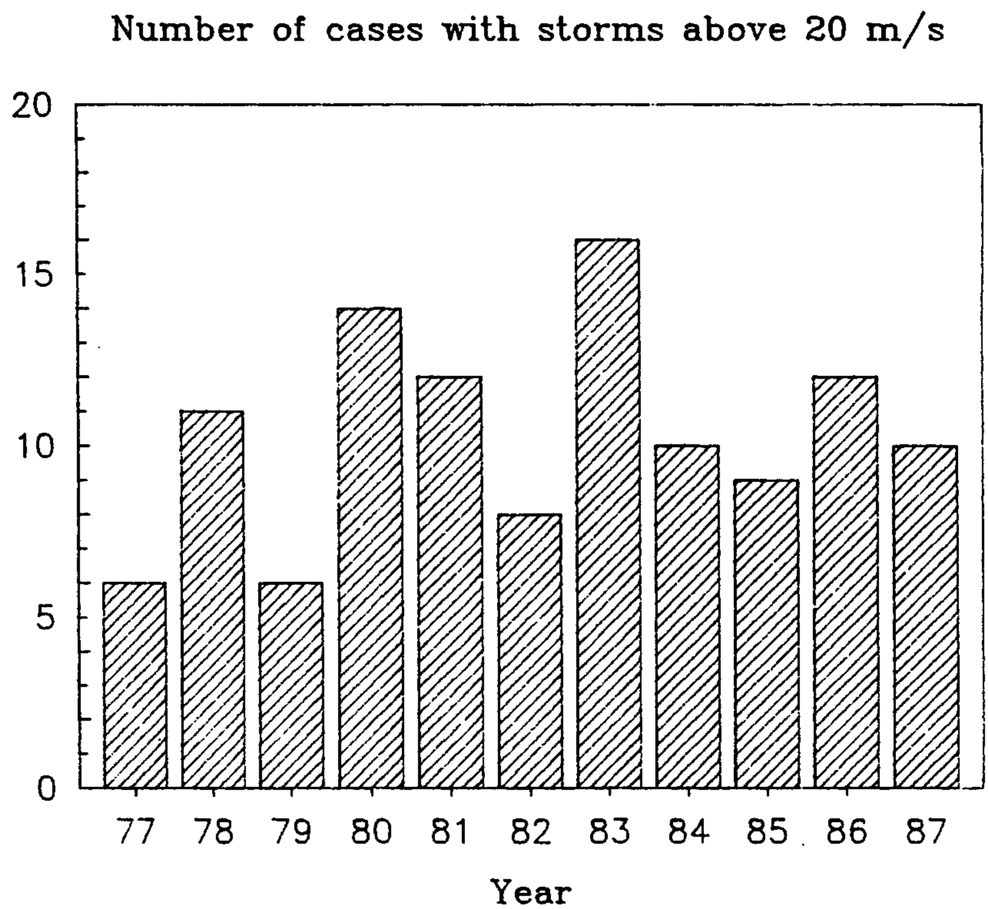

Figure 1: Number of cases with storms above 20 m/s.

For the reminder of this report it suffices to repeat that the data consist of 10-min consecutive averages and that only observations from the 70-m level are analysed.

2 Storm criteria

The beginning of a storm is indicated by u exceeding the 14-m/s level; and is terminated when either of following criteria are fulfilled:

- $u <$ 14 m/s in the next 12 hours, or
- $u <$ 12 m/s in the next 6 hours, or
- $u <$ 9 m/s in 1 observation.

The termination is at the beginning of a period where any of the above criteria are fulfilled.

The event is only registered as a storm if the 16 m/s level is exceeded. For each storm event the maximum value of the wind projection across the bridge (assumed direction 257°– 77°) is also found. The entire record of storms contains the following information.

1. Time for extreme wind
2. Value of extreme wind
3. Direction of extreme wind
4. Value of extreme cross wind
5. Time for extreme cross wind
6. Start of storm
7. Termination of storm.

The above criteria may appear somewhat arbitrary and could of course have been otherwise chosen. However, in this context their sole significance is to give a suitable separation between events of high wind.

3 Storm events

Table 2 gives the 30 largest storm events according to the above criteria for each of 12 wind direction sectors (30° per sector, clockwise direction; 0, north; 3, east; 6, south; 9, west!), and in the last column the overall 30 largest wind speeds. The largest wind speed in the tower is selected irrespective of height and wind direction.

At this point we have not analysed the extremes for each of the wind directions, but concentrated on the overall statistics only.

Table 2: The 30 largest storm events (m/s) for each wind direction sector, and irrespective of direction (All).

Sector:	0	1	2	3	4	5	6	7	8	9	10	11	All
1.	22.36	19.49	22.66	23.06	27.28	22.50	25.48	26.77	28.44	29.07	29.05	25.01	29.07
2.	20.16	18.92	20.66	21.48	25.72	20.86	21.34	24.40	26.47	27.69	26.51	24.53	29.05
3.	19.98	18.49	19.00	19.25	23.28	20.56	21.27	24.09	25.06	27.21	25.72	24.40	28.44
4.	18.49	18.35	18.25	19.02	21.75	20.26	20.97	21.99	24.91	25.55	24.50	23.34	27.69
5.	18.45	18.25	17.72	18.15	21.41	20.10	20.39	21.89	24.36	23.78	24.23	22.70	27.28
6.	18.42	18.02	16.41	18.11	21.27	19.78	20.26	21.78	23.58	22.09	23.97	22.05	27.21
7.	18.39	16.99	16.11	18.05	20.83	19.59	20.02	21.48	23.41	22.05	23.65	21.48	26.77
8.	18.38	16.88	0.00	18.04	20.19	19.13	19.74	21.33	23.17	21.39	23.51	21.41	26.51
9.	17.93	16.77	0.00	17.98	19.37	18.83	19.54	21.07	22.53	21.34	23.38	21.31	26.47
10.	17.36	16.58	0.00	17.43	19.23	18.76	19.44	21.07	21.42	21.03	23.21	21.10	25.72
11.	17.30	16.35	0.00	17.26	19.20	18.55	19.19	21.03	21.20	20.76	22.39	20.93	25.72
12.	17.23	0.00	0.00	17.26	19.20	18.03	18.89	21.02	20.49	20.32	22.29	20.90	25.55
13.	16.62	0.00	0.00	17.23	19.17	18.01	18.76	20.86	20.42	20.08	21.90	20.29	25.48
14.	16.62	0.00	0.00	17.16	19.12	17.53	18.72	20.56	20.39	19.99	21.67	20.22	25.06
15.	16.48	0.00	0.00	16.75	19.00	17.46	18.59	20.52	20.36	19.89	21.54	19.57	25.01
16.	16.24	0.00	0.00	16.41	18.95	17.28	18.55	20.29	20.15	19.72	21.44	19.52	24.91
17.	16.19	0.00	0.00	0.00	18.93	17.23	18.21	19.99	19.98	19.51	21.41	18.96	24.53
18.	16.14	0.00	0.00	0.00	18.86	17.16	17.94	19.98	19.95	19.40	21.37	18.89	24.50
19.	16.07	0.00	0.00	0.00	18.55	17.09	17.70	19.92	19.81	18.79	21.09	18.76	24.40
20.	0.00	0.00	0.00	0.00	18.52	16.75	17.60	19.81	19.57	18.76	20.86	18.72	24.40
21.	0.00	0.00	0.00	0.00	18.52	16.31	17.57	19.62	19.16	18.73	20.79	18.08	24.36
22.	0.00	0.00	0.00	0.00	18.35	16.31	16.99	19.53	19.13	18.72	20.56	17.70	24.23
23.	0.00	0.00	0.00	0.00	18.18	16.18	16.99	19.03	18.89	18.08	20.56	17.33	24.09
24.	0.00	0.00	0.00	0.00	18.08	0.00	16.98	19.02	18.83	18.08	20.49	17.20	23.97
25.	0.00	0.00	0.00	0.00	18.01	0.00	16.95	18.99	18.38	18.04	20.46	16.75	23.78
26.	0.00	0.00	0.00	0.00	18.01	0.00	16.85	18.76	18.21	17.81	20.36	16.65	23.65
27.	0.00	0.00	0.00	0.00	17.77	0.00	16.82	18.72	18.21	17.77	20.22	16.55	23.58
28.	0.00	0.00	0.00	0.00	17.67	0.00	16.79	18.62	18.18	17.77	20.15	16.41	23.51
29.	0.00	0.00	0.00	0.00	17.55	0.00	16.72	18.46	18.02	17.70	20.02	16.31	23.41
30.	0.00	0.00	0.00	0.00	17.50	0.00	16.69	18.42	17.77	17.55	19.78	16.29	23.38

4 Extrapolation to the 50-year storm

It is assumed that the double exponential, the so-called Gumbel (1958) distribution, is the relevant description of the frequency of extreme events (see e.g. Cook, 1985).

In Fig. 2 we have therefore shown the rightmost column of Table 2 versus the double-log of its relevant probabilities:

$$P = \frac{m}{N+1} \tag{1}$$

where N is the size of sample, in this case 30 and m is an ordering number of the ranked events (for the largest event $m = N$). The points are seen to follow a straight line pretty well. The line shown has the regression

$$u = 1.48\,x + 24.60 \qquad x = -\ln\left(-\ln\frac{m}{31}\right) \tag{2}$$

where the numerical values for the slope α and the off-set β assume that u is in m/s.

We shall take the value of the regression line for $m = 30$ as our estimate for u_{10}, the wind speed that on the average will be exceeded once every 10 years (note the remark in the introduction).

The double exponential form of the accumulated probability function implies that for large (and rare) events, the *pdf* itself is an exponential, $p \approx \exp(-x)$. For such processes it can be shown that the average number of exceedances per unit time η_1 of a certain speed u_1 is proportional to $p(u_1)$. (see e.g. Jensen amd Kristensen, 1989). This can be used to extrapolate the above to another "return period" T. Thus, for one exceedance on the average $T_1 \cdot \eta_1$ is constant:

$$T_1\,e^{-x_1} = T_2\,e^{-x_2}\ , \qquad (u = \alpha x + \beta) \tag{3}$$

or

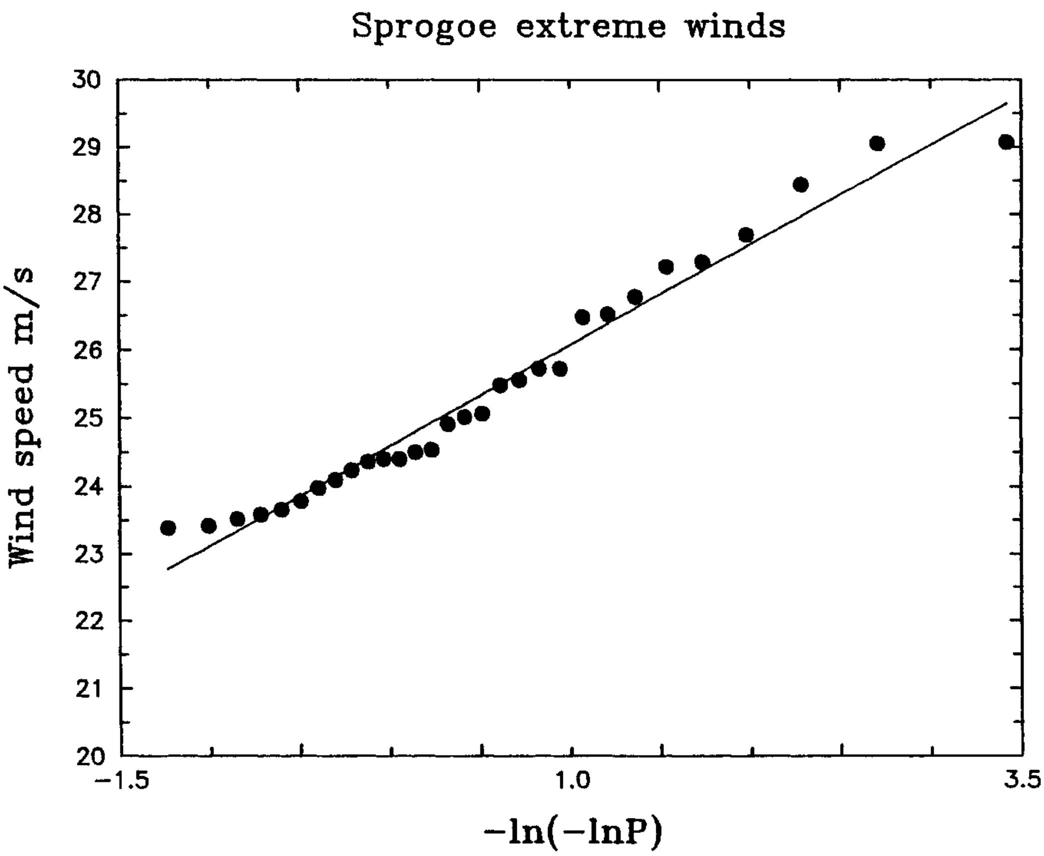

Figure 2: Sprogø extreme winds, irrespective of direction (see Table 2).

$$u_2 = u_1 + \alpha \ln \frac{T_2}{T_1} \quad . \tag{4}$$

With T_2 and T_1 equal to 50 and 10 years, respectively, this leads to

$$u_{50} = u_{10} + \alpha \ln 5 \quad . \tag{5}$$

The numerical value of the above is $u_{50} = 32.0$ m/s. The significance of this estimate is discussed below but first we discuss a couple of other estimation strategies.

In order to completely circumvent the seemingly arbitrary definition of a storm event, a second entirely independent method has been applied. We have simply selected the highest wind speed value once a month. Furthermore, the selection has been subject to a criterion selecting only the upwind anemometer at the 70-m level (Jensen and Troen, 1989). Figure 3 shows the plotting of the ensuing values. The line shown has the regression

$$u = 1.69 \cdot x + 23.50 \tag{6}$$

and is of course different from the storm regression (Eq. (2)), since the selection is made from a different criterion (some cases with more than one storm per month have been neglected). However, the extrapolation to a 50-year average return value is the same as above, see Table 3). A third method based on extrapolation of u-squared, or the wind pressure, is also included (Fig. 4) and gives a consistent but slightly lower estimate of u_{50} (see Table 3).

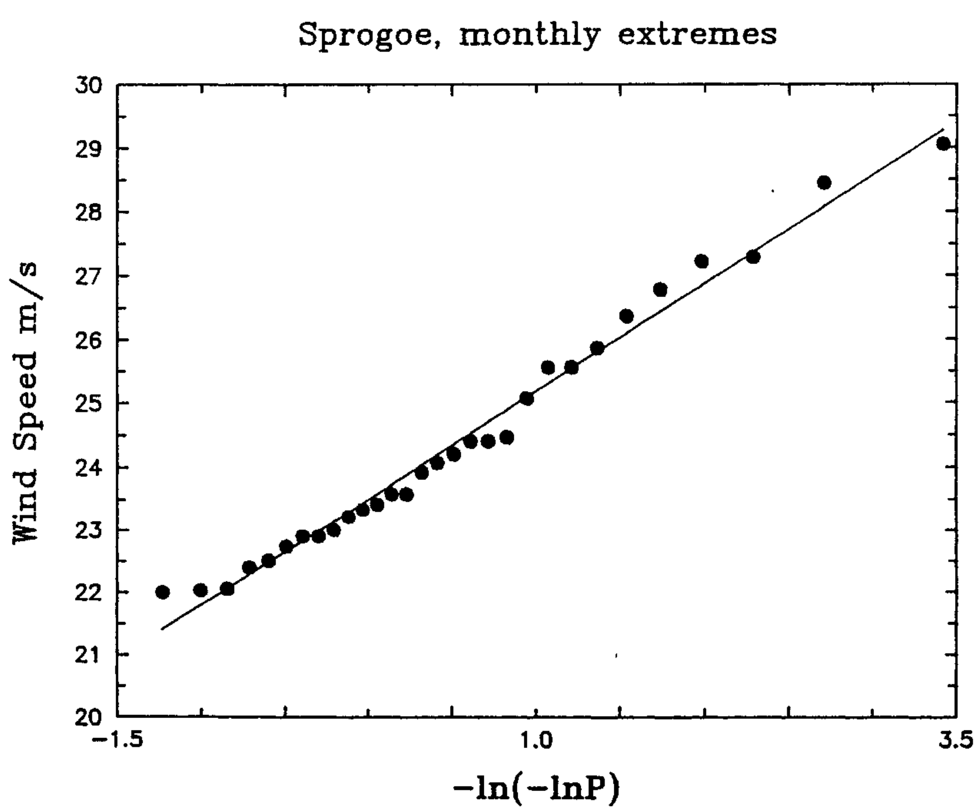

Figure 3: Sprogø, monthly extremes, irrespective of direction.

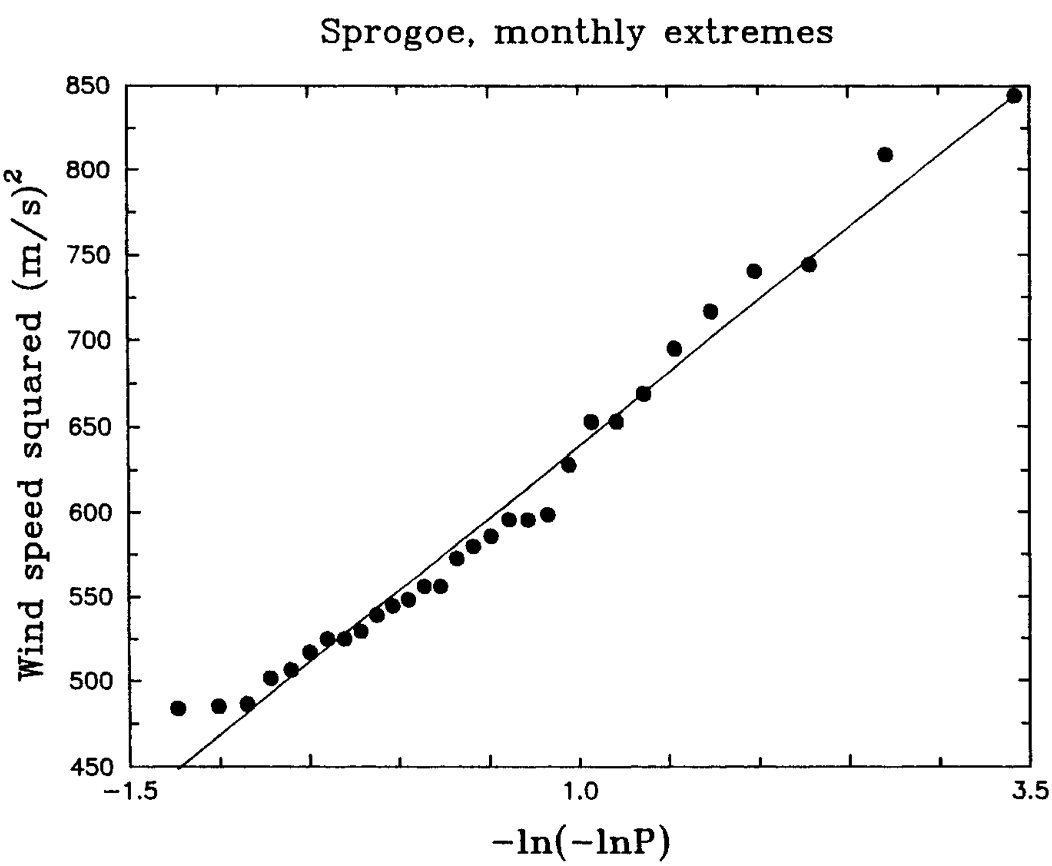

Figure 4: Regression based on dynamic wind pressure .

5 Discussion of the 50-year wind

The present analysis gives an appreciably smaller design wind than the Danish Wind Code (The Danish Association of Civil Engineers, 1978). Straight application of the latter for the 70-m level over water gives

$$u_{50} = 27 \cdot 0.17 \ln \frac{70}{0.01} = 40.6\,\mathrm{m/s} \tag{7}$$

to be compared with the present estimate of 32 m/s.

According to the best estimates, our 32 m/s corresponds to a surface friction velocity u_* and a surface roughness z_0 of the Great Belt of 1.64 m/s and 2.35 $\cdot 10^{-3}$ m, respectively. For details, see Jensen and Kristensen (1989).

Extrapolating this in the wind-atlas fashion (Troen et. al., 1987) to conditions 10-m above a land surface with a 5 cm roughness gives approximately $u =$ 22 m/s, to be compared to the 27 m/s of the Code.

Table 3: Summary of extreme value fitting.

	α	β	u_{10} m/s	u_{50} m/s
Storm citerion	1.48	24.60	29.7	32.0
Monthly extreme	1.69	23.50	29.3	32.0
Pressure	85.09	593.6	29.1	31.3
Cross wind	1.24	20.59	24.8	26.8

We have no intention of debating the accuracy of the Danish Wind Code. However, we have searched in relevant data records and found no measured wind speeds exceeding our estimates. According to Risø records the closest call is two consecutive 10-min average velocities (10 m above open farmland) measured near Stigsnæs on 24 November 1981. The velocity was 21.6 m/s. The largest wind speed on record from the 32-year long history of the Risø tower (72-m level) is an *estimated* 33 m/s from direction 290°. From this direction the wind is subject to a slight (6-7%) terrain-induced overspeed (Jensen and Peterson, 1978).

6 Crosswind extremes

As mentioned in Section 2 we also accumulated the maximum values of the wind projection across the bridge.

Table 4: Crosswind distribution.

Sector:	0	1	2	3	4	5	6	7	8	9	10	11	All
speed range (m/s)													
0 – 2	0	0	0	0	0	0	0	0	0	0	0	0	0
2 – 4	0	0	0	1	0	0	0	0	1	2	0	0	4
4 – 6	0	0	0	0	0	0	0	0	0	6	0	0	6
6 – 8	0	0	1	4	0	0	0	0	10	7	0	0	22
8 – 10	0	0	2	7	2	0	0	0	15	10	1	0	37
10 – 12	0	1	2	3	4	0	0	7	10	9	4	0	40
12 – 14	0	2	0	1	22	0	0	21	7	10	29	0	92
14 – 16	6	5	1	0	23	3	7	16	5	7	23	8	104
16 – 18	7	2	1	0	5	13	16	15	6	3	20	8	96
18 – 20	5	1	0	0	2	6	11	4	2	0	5	10	46
20 – 22	0	0	0	0	0	1	2	1	2	1	3	4	14
22 – 24	1	0	0	0	1	0	0	1	0	0	0	2	5
24 – 26	0	0	0	0	0	0	1	0	0	0	0	2	3
26 – 28	0	0	0	0	0	0	0	0	0	0	0	0	0
28 – 30	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 4 gives the number of occurrences in the various bins of wind speed according to direction of the absolute wind speed maximum during the storm events previously identified. A sinusoidal pattern is discernible with a maximum occurrence of large speeds at directions perpendicular to the direction of the bridge (257 - 77°). The crosswind maxima $\hat{u}$ are ranked in Table 5, and Fig. 5 shows the plotting. The extrapolated extreme value is $\hat{u}_{50} = 26.8$ m/s (see Table 3).

Table 5: The 30 largest crosswind events (m/s) for each sector of the absolute maximum event.

Sector:	0	1	2	3	4	5	6	7	8	9	10	11	All
1.	22.02	18.42	16.47	12.80	22.89	21.52	24.22	23.12	21.93	20.91	21.70	24.15	24.22
2.	19.36	16.54	14.96	11.24	19.95	19.81	20.50	20.80	20.74	17.69	20.88	24.02	24.15
3.	18.48	16.04	11.55	10.70	19.55	19.58	20.34	19.82	19.92	16.38	20.33	23.28	24.02
4.	18.35	15.93	10.69	10.10	17.55	19.54	19.42	19.73	18.23	16.09	18.91	22.47	23.28
5.	18.34	15.47	8.31	9.98	17.50	18.89	19.33	18.15	17.63	15.56	18.89	21.04	23.12
6.	18.15	15.33	8.30	9.48	17.04	18.66	19.27	18.07	17.55	15.25	18.85	20.97	22.89
7.	17.83	14.24	6.73	9.24	16.99	18.52	19.11	17.90	17.39	15.06	18.65	20.93	22.47
8.	17.66	14.23	0.00	8.92	16.29	17.58	18.87	17.72	17.32	14.97	18.34	20.58	22.02
9.	17.36	13.09	0.00	8.81	15.82	17.55	18.61	17.50	16.91	14.92	17.99	19.91	21.93
10.	17.18	13.03	0.00	8.48	15.78	17.15	18.54	17.43	16.64	14.40	17.97	19.27	21.70
11.	16.98	10.62	0.00	8.18	15.58	17.08	18.53	17.38	15.25	14.24	17.90	19.21	21.52
12.	16.61	0.00	0.00	7.94	15.48	17.06	18.45	17.20	14.89	13.82	17.87	18.91	21.04
13.	16.02	0.00	0.00	7.45	15.42	16.75	18.24	16.98	14.65	13.80	17.61	18.84	20.97
14.	15.99	0.00	0.00	6.15	15.32	16.69	18.10	16.96	14.37	13.77	17.61	18.80	20.93
15.	15.96	0.00	0.00	6.10	15.30	16.61	17.88	16.93	14.17	13.71	17.48	18.47	20.91
16.	15.78	0.00	0.00	3.88	15.29	16.37	17.35	16.88	13.62	13.49	17.41	18.44	20.88
17.	15.58	0.00	0.00	0.00	15.28	16.34	17.30	16.48	13.47	13.28	17.40	18.19	20.80
18.	15.47	0.00	0.00	0.00	15.03	16.30	16.96	16.38	12.86	13.06	17.36	18.00	20.74
19.	14.88	0.00	0.00	0.00	15.02	16.17	16.95	16.38	12.45	12.66	17.17	17.64	20.58
20.	0.00	0.00	0.00	0.00	14.89	16.05	16.91	16.27	12.34	12.27	17.05	17.56	20.50
21.	0.00	0.00	0.00	0.00	14.76	15.03	16.91	16.08	12.30	12.20	16.92	17.38	20.34
22.	0.00	0.00	0.00	0.00	14.70	14.79	16.78	15.81	12.15	11.83	16.86	17.06	20.33
23.	0.00	0.00	0.00	0.00	14.47	14.27	16.77	15.74	11.78	11.66	16.86	16.87	19.95
24.	0.00	0.00	0.00	0.00	14.40	0.00	16.75	15.47	11.73	11.59	16.85	16.38	19.92
25.	0.00	0.00	0.00	0.00	14.39	0.00	16.58	15.45	11.71	11.35	16.45	16.19	19.91
26.	0.00	0.00	0.00	0.00	14.36	0.00	16.49	15.25	11.22	10.55	16.39	16.10	19.82
27.	0.00	0.00	0.00	0.00	14.34	0.00	16.42	15.20	11.21	10.45	16.02	15.94	19.81
28.	0.00	0.00	0.00	0.00	14.18	0.00	16.14	14.85	10.49	10.42	16.01	15.64	19.73
29.	0.00	0.00	0.00	0.00	14.14	0.00	16.05	14.57	10.34	10.13	15.84	15.60	19.58
30.	0.00	0.00	0.00	0.00	14.04	0.00	16.01	14.56	10.17	10.10	15.80	15.22	19.55

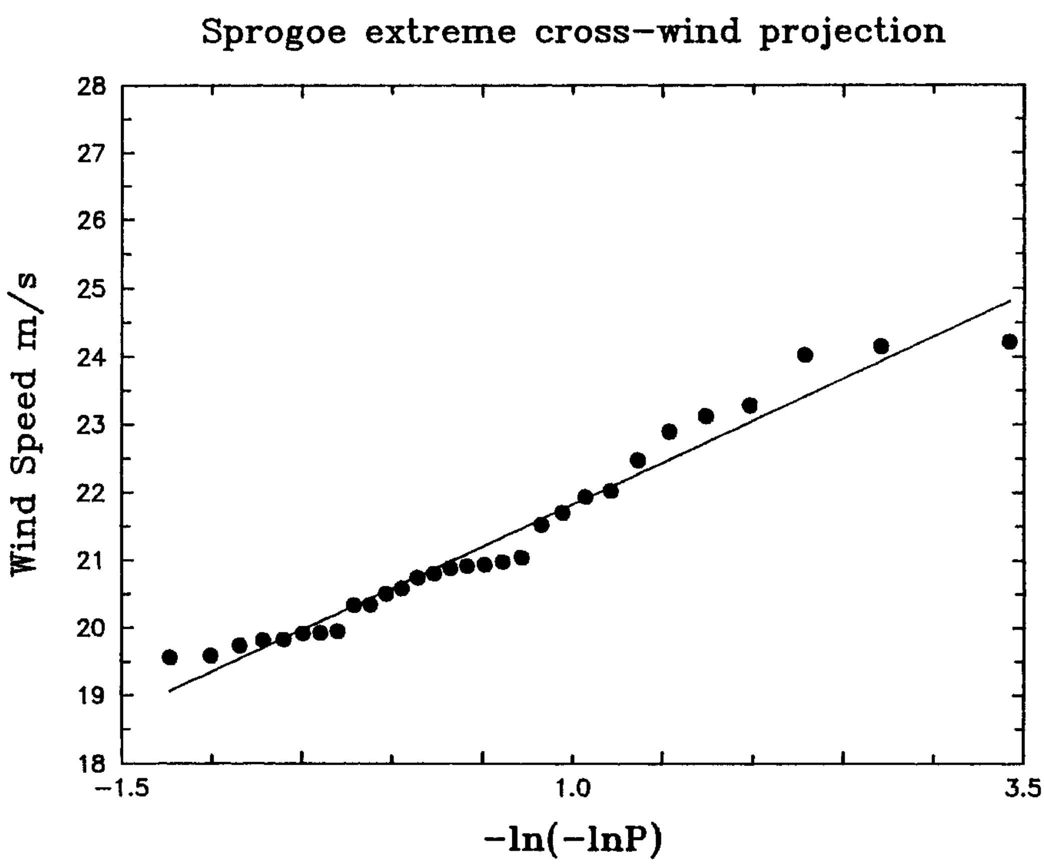

Figure 5: Sprogø extreme crosswind projection.

7 Conclusion

We have analysed the occurrence of large wind speeds at the 70-m level above water in the Great Belt. The period analysed is a little more than 10 years. The largest 10-min average velocity measured in this period is 29.07 m/s. This sample would not have passed the more selective criteria used for selecting the largest monthly value and in general (Jensen and Troen, 1989). It occurred under northwesterly wind at the *downwind* anemometer, signifying an overspeeding effect in the tower wake. When the measurements are extrapolated on the basis of a Gumbel distribution, we find that the wind speed, exceeded on the average only once in 50 years, is 32 m/s. This is considerably less than the prescription in the Danish Wind Code. Regarding the crosswind component (relative to the bridge) the corresponding value is 26.8 m/s.

Symbols

u Wind speed averaged over 10 min

u_{10} Wind speed which on the average will be exceeded every 10 years

u_{50} As above, but for 50 years

m Ordering number

N Sample size

p Accumulated probability

α Slope of regression line

β Off-set of regression line

T Return period: the time in which on the average a Poisson proces gives one exceedance of a certrain threshold.

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Abstract (Max. 2000 char.)

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